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Abstract

The major advances achieved during African monsoon multidisciplinary analysis in our physical understanding of the West African monsoon (WAM) system are reviewed. Recent research provides an advanced understanding of key WAM features. The Saharan heat low, the interactions of the monsoon flow with the surface and the reversed flow on top of it, all play a more important role than previously assumed, and interact according to the phase of the diurnal cycle of convection. Recent studies also emphasise the significance of upstream conditions in Central and East Africa, as well as strong interactions between midlatitudes and the WAM. Copyright © 2011 Royal Meteorological Society

Keywords: African monsoon; heat low; African easterly jet; convection; atmospheric boundary layer; tropical-extratropical interactions

1. Introduction

The poor skill of general circulation models (GCMs) and numerical weather prediction (NWP, see also Fink *et al*., 2011) models in capturing the characteristics of the West African monsoon (WAM), notably its associated precipitation pattern and variability, motivated the international African monsoon multidisciplinary analysis (AMMA) programme. Through its multi-scale approach, AMMA promoted the idea that a better knowledge of the complex chain of physical processes that act on different spatial and temporal scales and that result in precipitating weather systems is necessary to improve their representation in GCM and NWP models. The special observation periods (SOP) in 2006 are one aspect of this effort (Lebel *et al*., 2010), whose current scientific exploitation has fostered research to document and understand the functioning of the WAM system, involving numerous couplings between the atmosphere, the continental surface and the ocean.

After a presentation of the conceptual model which was in use before AMMA (Section 2), we review in Section 3 the main findings of the three AMMA years after the SOPs, to physically understand the WAM system and the weather systems embedded within it. Section 4 presents conclusions.

2. WAM conceptual model before AMMA

Figure 1 highlights some of the key features of the WAM system that are described in some detail in Lafore *et al*. (2010). Only the features pertinent to the findings described here are replicated; the Saharan heat low (SHL) corresponds to a deep, dry-convective atmospheric boundary layer (ABL) (red dome in Figure 1). The SHL pressure minimum located on its southern flank drives the convergence of two opposing low-level flows along the inter-tropical discontinuity (ITD, dashed blue line in Figure 1): i.e. the northerly dry and hot flow and the south-westerly moist and cooler monsoon flow. The resulting strong baroclinicity across this discontinuity, together with associated contrasts in convection (moist to the south and dry to the north), is responsible for the midlevel African easterly jet (AEJ, yellow tube in Figure 1), with its core located around 600 hPa.

African easterly waves (AEWs) are the major synoptic weather systems in the WAM. These originate

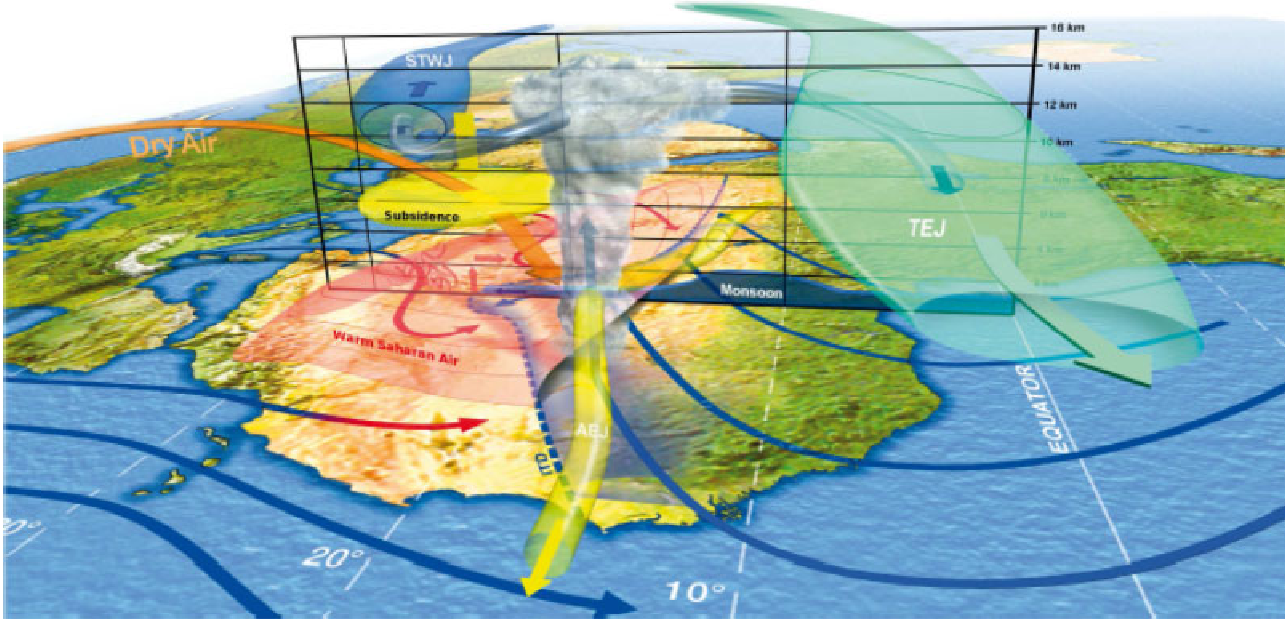

Figure 1. Three-dimensional schematic view of the WAM. ITD, inter-tropical discontinuity; TEJ, tropical easterly jet; STWJ, subtropical westerly jet; AEJ, African easterly jet. The oscillation of the AEJ yellow tube figures an African easterly wave [from Lafore *et al.* (2010)].

east of 20 °E and develop through barotropic and baroclinic energy conversions as they move along the AEJ. Their wavelength (2000–4000 km) and westward propagation (~8 m s^{-1}) result in periods between 3 and 5 days. AEWs interact strongly with moist convection, but a complete understanding of these interactions is still lacking.

Due to strong baroclinicity and gradient of humidity as discussed in Parker *et al.* (2005a), convection is organized, and maximised, in the Inter-tropical convergence zone (ITCZ), located at and south of the latitude of the AEJ and about 10° to the south of the ITD. When active, the associated upper-level anticyclonic and divergent flow feeds the tropical easterly jet (TEJ) and subtropical westerly jet (STWJ). Fast-moving mesoscale convective systems account for most of the rain over the Sahel (~12–18 °N) and about half of the rain in the wetter Soudanian zone (~9–12 °N). They are also the main source of long-lived cirrus ice clouds, which strongly modulate the radiative balance in the WAM region. The understanding, forecasting and representation in models of MCSs and their interplay with large-scale features of the WAM remain major challenges.

3. A new perspective on the physics and dynamics of weather systems in the monsoon

Prior to AMMA, the 'textbook' vision of the monsoon system, outlined in Section 2, showed some features which, in the study of climates of other parts of the world, would have been regarded as outmoded. Notably, there has been rather a crude 'airmass' picture of the thermodynamics in the monsoon, while in contrast AMMA has exposed the critical importance of mixing and exchange between the different layers shown in Figure 1, modulated by the diurnal cycle. Likewise, the relatively simplistic picture of synoptic systems growing as normal-mode instabilities has long been criticised in the study of midlatitude dynamics, but was still prevailing in discussions of the monsoon. As well as bringing our understanding of the WAM system up to speed with modern dynamical concepts, AMMA has also provided new and innovative understanding of the dynamics of weather and climate over the tropical continents, particularly in our understanding of the continental moisture budgets over a range of climatic zones, in the appreciation of the larger-scale role of convective cold pools and in a new awareness of the interaction of tropical continental dynamics with midlatitude systems.

The schematic representation in Parker *et al.* (2005a) provides a view of the vertical structure of the WAM with a strong meridional contrast of the ABL depth reflecting the strong moisture and temperature gradient of surface conditions. Through AMMA, we now recognise the significance of the diurnal cycle of the ABL in the weather and climate of the whole continent: over the Sahara the ABL makes up around 50% of the mass of the troposphere, and the diurnally-evolving heat low is a major control on the whole North African circulation. Further in south, in the Sahel, there are strong seasonal and meridional contrasts in the ABL (Saïd *et al.*, 2010), and large mesoscale fluctuations (Taylor *et al.*, 2007) which feed back on the atmospheric circulation. For instance, daytime surface heating and convective boundary layer (CBL) growth are found to directly influence the diurnal cycle of the AEJ prior to the monsoon onset; this leads to a diurnal cycle of its speed which is out of phase with the diurnal cycle of the SHL (Kalapureddy *et al*., 2010).

Prior to the monsoon onset, the Sahelian CBL is usually deep and displays remarkable features, such as very large daytime upward transport of moisture and drying of the mixed layer, which restricts convective cloud development (Canut *et al*., 2010). Conversely, during the full monsoon, the CBL is much shallower, moister, and ABL clouds become more prominent. These contrasting low-level features are difficult to simulate accurately, because they involve various subtle balances among coupled processes. For instance, Guichard *et al*. (2009) show that night-time turbulence is affected by the reduction of surface net longwave flux induced by the radiative properties of the moist monsoon flow. AMMA has provided the observations with which to test model representation of these balances, and the work is ongoing.

The full diurnal cycle of the monsoon flow has been documented (Parker *et al*., 2005b; Lothon *et al*., 2008; Abdou *et al*., 2010). This shows that the nocturnal flow dominates the moisture budget in the Sahel around the time of the monsoon onset and is associated with a strong low-level jet, with its peak around 400 m in altitude. This nocturnal flow is also associated with northward motions of the ITD (Pospichal *et al*., 2010). During daytime, boundary layer convective mixing leads to a thickening of the monsoon flux and to a reduction of low-level monsoon winds. After the monsoon onset, the MCS-generated cold pools also contribute to shape the northward propagation of the ITD (Flamant *et al*., 2007, 2009).

For the first time, the SOP allowed a detailed documentation of the Saharan ABL (SABL). Cuesta *et al*. (2008) and Messager *et al*. (2010) show that the daytime SABL exhibits a remarkable split structure, with a well-mixed convective layer beneath a residual layer whose dynamics appears to be nearly laminar. This residual layer is on some days and in some places mixed into the CBL. Cuesta *et al*. (2009) have built a comprehensive view of the dynamical mechanisms controlling the vertical redistribution of dust and the thermodynamic structure of the SABL during the summer. They show evidence that the two-layer structure of the SABL is sustained by various mesoscale processes, including lifting at the ITD, as well as hot plumes ascending rapidly through the boundary layer over topographic features such as hills or dark rocks. More quantitative measurements of these Saharan processes will be needed in order to test and improve model performance for the region.

Lavaysse *et al*. (2009) proposed an objective method to detect the SHL and analysed its seasonal cycle. They confirmed a link between the monsoon onset and the onset of the SHL over the Sahara in the summer and in the beginning of the rainy season over the Sahel that was earlier suggested in modelling studies by Ramel *et al*. (2006) and Sijikumar *et al*. (2006). For the period before the onset, Couvreux *et al*. (2010) highlighted variability at a 3–5-day time scale of the monsoon flow, characterised by successive northward excursions. SHL reinforcement appears as the driving mechanism of those monsoon surges (as proposed by Parker *et al*. (2005b)) followed by cool low-level 'ventilation' of the SABL. After the monsoon onset, these 'monsoon surges' still occur but are coupled with enhanced convective activity. Cuesta *et al*. (2010) provided intriguing examples of intense rainfall events over the Hoggar Massif, where monsoon surges have been identified as the controlling factor. Similarly, Grams *et al*. (2010) discuss the sea breeze-like inflow of cool and stably stratified air from the Atlantic via Mauritania into the southwestern part of the SHL. This so called Atlantic Inflow is another part of the ventilation process that controls the heat and moisture budgets of SHL and the monsoon penetration (Peyrillé and Lafore, 2007).

A body of AMMA work has revealed strong interactions between the tropics and extra-tropics, and variability in the SHL is one key element of this interaction. Knippertz and Fink (2008) investigated the dynamics of an unusual, high-impact precipitation event in tropical West Africa that was preceded by the enhancement of the winter-time SHL in relation to two subtropical troughs and a persistent cloud band. The strengthened SHL caused moist southerlies to penetrate, unusually far, into the continent. Such extratropically forced events possess at least a moderate forecast skill about a week ahead (Knippertz and Fink, 2009) and may modulate the convective activity and organisation. Vizy and Cook (2009) emphasised a mechanism by which Mediterranean cold air surges can influence North African and East Sahelian weather systems. Chauvin *et al*. (2010) showed that such cold air surges are related to an intraseasonal mode of variability of the SHL, excited by large-scale midlatitude intraseasonal fluctuations of the atmosphere. This mode was statistically related to convective anomalies over the eastern Sahel. Lavaysse *et al*. (2010) analysed the intraseasonal variability of the SHL and demonstrated the impact of midlatitude circulations in the 10–30-day period band. A midlatitude impact on Sahel convection that is less clearly related to summertime SHL variability are 'dry intrusion' events in the mid-troposphere over the Sahel (Roca *et al*., 2005).

On the synoptic scales, our view of the genesis of AEWs has been advanced by the studies of Hall *et al*. (2006) and Thorncroft *et al*. (2008). Owing to the weak or neutral linear instability of the AEJ, and its limited zonal extent relative to theoretical growth rates of wave modes, they view AEWs as a response to an enhancement of convection at the jet entrance over the Darfur region. Further results by Leroux and Hall (2009) attest that the wave response is also sensitive to the jet structure, with a broader and stronger AEJ favouring more intense AEWs. Leroux *et al*. (2010) investigated the observed relationship between the AEJ, AEWs and convection at intraseasonal scales. Episodes of enhanced AEW activity are preceded by an upstream intensification of the AEJ, and followed by a downstream shift of the AEJ to the north, consistent with transient momentum fluxes by the AEWs. Barthe *et al.* (2010) and Cuesta *et al.* (2010) investigated the multi-scale processes associated with a sequence of convective events over Niamey, corresponding to an intense monsoon surge and to the passage of a strong AEW. MCSs act to reduce the monsoon flow and to generate southerlies at midlevels, which can enhance the rotation of the wind at the AEW trough passage. Nevertheless, further studies are needed to understand better the link between monsoon surges and the AEWs.

A major downstream impact of the WAM is the genesis of tropical cyclones from convection embedded within an AEW. Model case studies quantified the differing interactions between convection and the AEW both over land and the ocean for developing and non-developing systems (Arnault and Roux, 2009, 2010; Schwendike and Jones, 2010). In the Cape Verde Islands region, east of 30 °W, barotropic energy conversions over the ocean were crucial for the cyclogenesis event, but were inhibited by the presence of a large anticyclonic circulation of Saharan origin in the non-developing case. A low-level circulation originating in the SHL contributed to the tropical cyclogenesis. Once again, the circulations occurring in the active boundary layer are crucial for the dynamics of larger-scale systems.

AMMA has made considerable progress in studying the interactions of moist convection with the larger-scale circulation, but much work remains to be done. During the 4 months of SOPs, many convective events were sampled by a wide variety of platforms at different scales that additionally have allowed us to study MCS dynamics as well as cloud microphysical and radiative properties (Bouniol *et al.*, 2010; Chong, 2010; Evaristo *et al.*, 2010; Gosset *et al.*, 2010; Penide *et al.*, 2010; Protat *et al.*, 2010). These microphysical studies are the basis of ongoing cloud-resolving model approaches with which we aim to improve the ability of models to handle convective microphysics in the range of tropical environments. West Africa is one of the most lightning-active parts of the world, for reasons which are not well understood. The structure of lightning within thunderstorms was documented for the first time by the lightning detection network (LINET) set up in Benin (Höller *et al.*, 2009). One pertinent result is that, relative contribution of ground strokes to the overall stroke count was large compared to other tropical regions.

4. Conclusions

This review shows that the AMMA research programme has led to significant improvements of our physical understanding of the WAM system for each of its key components and also of their couplings with the land surface, aerosols and ocean (see Taylor *et al.*, 2011, Marticonera *et al.*, 2011, and Brandt *et al.*, 2011, respectively). We have achieved major progress concerning the ABL, the heat low, the AEJ and AEWs, including their interactions. No significant advance was, however, achieved in understanding the role of the TEJ in the complex interaction between synoptic-scale features (e.g. AEWs) and convection. A considerable impact of the midlatitudes on convection in the WAM area has been demonstrated; in particular, involving variations in the heat low position and intensity at synoptic to intraseasonal time scales (Janicot *et al.*, 2011). This midlatitude impact promises an exploitable skill in predicting WAM onset and break periods.

However, further analysis of case studies from the SOP, but also climatological and modelling studies, are needed to analyse these interactions; including the role of the heat low in the interaction chain, and their contribution to the WAM intraseasonal variability. As one first step towards this direction, we recommend continuing to perform cloud-resolving model and large eddy simulations of specific cases in order to evaluate parameterisations used by GCMs (see Ruti *et al.*, 2011). In another second step we encourage research to improve the representation of processes relevant to the WAM and heat low and lacking in current parameterisations, such as density currents (Grandpeix and Lafore, 2010).

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